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FINAL TECHNICAL REPORT TO THE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Grant No. USAF-AFOSR-85-0230

"Quantum Limits of Superconducting Heterodyne Receivers"

Period: May 15, 1985 - May 14, 1988

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Overview

An investigation of the behavior of superconducting heterodyne receivers in the quantum limit can be carried out using very low leakage tunnel junctions and relatively low frequencies, such as W-band. Alternatively, very low capacitance small-area junctions with moderate leakage can be used at much higher frequencies. It is necessary in either case to make precise measurements of mixer noise and gain. It is also essential to make precise determinations of the embedding admittances in order to permit comparison between experiment and theory. In addition, extensive computer software must be written in order to carry out the comparisons with quantum mixer theory.

In this project, the technology has been developed for both approaches to the study of the quantum limits of SIS heterodyne mixers. All of the factors necessary to make these comparisons in a W-band waveguide mixer have been in place since early 1977. Due to delays in the production at Yale of the special low leakage tunnel junctions required, however, the measurements were postponed until late 1988.

Much more extensive development of lithographed quasioptical mixers was necessary for the high frequency approach. Measurements of mixer performance in the quantum limit began at the end of the third grant year and were continued throughout 1988. Computer modeling began in mid-1988. A part of this program, which is testing small area junctions made at Berkeley will not begin until mid-1989.

Technology that is important for the optimization of practical SIS mixers for heterodyne receivers has been developed at every stage of this project and has been reported in a series of publications as well as invited and contributed papers at scientific meetings.

Summary of Progress

In collaboration with the Yale group, an extensive computer program was developed for theoretical modeling of SIS mixers. This program was used with considerable success to analyze measurements[10] made using a K_a-band mixer equipped with novel low-leakage Ta junctions.[13,16] Unfortunately, detailed testing of the quantum mixer theory could not be carried out because information about the embedding admittances in this mixer was not sufficiently accurate and because quantum effects were not sufficiently developed at this low frequency.

Under previous funding, construction had begun of a system designed to permit accurate measurements of mixer gain and noise at 90 GHz. Construction of this system was completed successfully.[4]

Tests were carried out on a W-band waveguide mixer block which can be tuned from 2.7 - 3.7mm (80-100 GHz) with a single mechanical adjustment.[3] This mixer block has been very well characterized by studies of large-scaled models so detailed theoretical modeling of quantum limited mixers should be possible. It also has very favorable properties for use in practical SIS receivers.[8,9,11] This mixer has an instantaneous bandwidth of ~3GHz and uses an IF transformer with high input impedance (500 - 700Ω). When used with $2x2(\mu m)^2$ Pb-based junctions from NBS Boulder this mixer gave a DSB gain of 8-12 dB, which is the highest ever seen in an SIS mixer. It also gave mixer noise temperatures of T_m (DSB) of 6-15K, which are the lowest yet observed at these frequencies.[12]

In order to observe strong quantum effects, arrangements were made to have tunnel junctions for this mixer fabricated at Yale using a Ta-Ta oxide-Pb technology which has extremely low leakage current.[5] The first such junctions received from Yale were tested, but gave very poor performance[14] because of an error in the optical lithography. Due to problems with personnel turnover in the Yale group, the next generation of junctions will not be available until 9/88, beyond the period of this grant. This delay has been very regrettable because the combination of Ta junctions and the well characterized W-band mixer block promises to give the first example of an SIS mixer operating strongly in the quantum limit. This work will be continued under the sponsorship of another agency.

The alternative approach to the observations of strong quantum effects is to use junctions with moderate leakage at near millimeter and submillimeter wavelengths. Since waveguide structures become very small and difficult to build at submillimeter wavelengths, a parallel development was carried out of SIS quasiparticle mixers with planar lithographed geometries. A quasi-optical test apparatus was developed[17] in order to evaluate such mixers at frequencies from 90 to 270 GHz. This apparatus includes cryogenic hot-cold loads at the IF in order to accurately measure mixer noise and gain. A special approach was devised for probing the DC response of quantum mixer junctions and an automatic computer fitting program was developed for comparing the DC response of pumped mixers to quantum theory in order to deduce accurate embedding admittances. These techniques were used to evaluate several types of planar lithographed mixer with bow-tie and log-periodic antennas at W-band. They included mixers made with a single junction, a single junction tuned with a microstrip stub, series arrays of 5 junctions, and series arrays of 5 junctions tuned with a parallel wire inductor. The mixers were fabricated at NBS Boulder using Pb-based and Nb-based junction technologies.

In all cases the measured coupling coefficient and the bandwidth agreed well with calculations based on simple equivalent circuits models and on the nominal parameters of the structures. Measurements were made of mixer gain and noise and comparisons were made to the performance of waveguide mixers with similar types of junction.[17] These comparisons indicate that there is a 6-7 dB loss between the cryostat window and the terminals of the bow-tie antenna. When corrected for this loss, the gains of the bow-tie mixers were comparable to the waveguide mixers, but the noises were higher by factors of 2-4.

Preparations were made for improvements in the optical system to reduce the input coupling losses. Tests of the improved system will be carried out under the sponsorship of another agency. Detailed computer modeling of the performance of these planar quasi-optical mixers was begun, but is being continued under other sponsorship.

The first steps were taken to operate planar quasi-optical SIS mixers at frequencies of 180 and 270 GHz. Harmonic generators were assembled which extended the frequency range of the quasi-optical mixer test apparatus. Planar lithographed mixers with quasi-optical RF matching structures were produced at NBS Boulder for operation at the second and third harmonic of W-band. A novel technique using the SIS junction as a direct detector and a Fourier transform infrared spectrometer as a source was used to evaluate the performance of these coupling structures.[15,18]

Preliminary results show good performance up to 180 GHz, and evidence of resonant RF coupling at 270 GHz. These experiments are being continued under other sponsorship.

The NBS junction technology could not produce junctions small enough to couple directly to submillimeter wavelengths. In order to produce such junctions a project was established with Prof. T. Van Duzer at Berkeley under the JSEP program. A student of Van Duzer's is fabricating very small Nb trilayer junctions with lithographed antennas and matching structures. He will then participate in measurements in my laboratory. These experiments will be carried out under other sponsorship.

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Personnel Associated with the Effort

1985-1986

D. G. Crété, Visitor
A. V. Räisänen, Visitor
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P. L. Richards, Professor
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C. Mears, Graduate Student Research Assistant

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P. L. Richards, Professor
Q. Hu, Postgraduate Research Physicst
C. Mears, Graduate Student Research Assistant

Interactions, Coupling Activities

Invited Talks

P. L. Richards, Josephson Junctions and SIS Detectors, ARO Workshop on Submillimeter Wave Detectors and Receivers, Minneapolis, MN, September 3, 1985.

P. L. Richards, Superconducting Receivers for Molecular Line Astronomy, March Meeting of the American Physical Society, Las Vegas, NV, 31 March-4 April 1986, Bull. Am. Phys. Soc. 31(3), 308 (1986).

P. L. Richards, Superconducting Quasiparticle Tunnel Junctions as Quantum Limited Detectors and Mixers for Microwave Radiation, Seminar, Department of Electrical Engineering and Computer Science, U.C. Berkeley, February 26, 1986.

P. L. Richards, SIS Mixers, West Coast Superconductive Electronics Meeting, Berkeley, CA, March 7, 1986.

P. L. Richards, Superconducting Microwave Heterodyne Receivers Approaching the Quantum Limit, Physics Department Colloquium, Stanford University, Palo Alto, CA, May 20, 1986.

D. W. Face, SIS Mixers in the Quantum Limit, March Meeting of the American Physical Society, 31 March-4 April 1986, Las Vegas, NV, Bull. Am. Phys. Soc. 31(3), 493 (1986).

P. L. Richards, Progress in the Development of SIS Quasiparticle Mixers, Applied Superconductivity Conference, Baltimore, Maryland, 9/28 - 10/3/86.

P. L. Richards, Superconductive Mixers, Air Force Applications of Cryoelectronics, Dayton, Ohio, October 30, 1986.

P. L. Richards, SIS Quasiparticle Mixers, Joint Services Electronics Programs Review, Berkeley, November 5, 1986.

P. L. Richards, RF Impedance Matching Structures for Planar SIS Mixers, Submillimeter (Terahertz) Receiver Technology Conference, Lake Arrowhead, Calif., April 7-8, 1987.

P. L. Richards, Superconducting Detectors, Seminar at Santa Barbara Research Center, Goleta, Calif., May 28, 1987.

P. L. Richards, Superconducting Detectors for Infrared and Microwaves, Seminar at Rockwell International Science Center, Thousand Oaks, CA, July 20, 1987.

Also at Hughes Aircraft Co., Space and Communications Group, El Segundo, CA, July 21, 1987.

P. L. Richards, Far Infrared and Submillimeter Devices, Seminar at the Radio Research Laboratory, Tokyo, Japan, February 3, 1988.

Also at the Advanced Telecommunications Research Institute International, Osaka, Japan, February 10, 1988.

P. L. Richards, Superconducting Detectors for Infrared and Millimeter Waves, Conference on Lasers and Electro-Optics (CLEO'88), Anaheim, CA, April 25, 1988.

Also at One Day Workshop on Superconductivity and Microwaves, 1988 IEEE MTT-S International Microwave Symposium, New York, N.Y., May 22, 1988.

Contributed Talks

A. V. Räisänen, W. R. McGrath, P.L. Richards, and F. L. Lloyd, A Simple Integrated Matching Element for SIS Quasiparticle Mixers, IEEE 1985 MTT-S International Microwave Symposium, St. Louis, Mo., June 4, 1985.

D. W. Face, D. E. Prober, W. R. McGrath, and P. L. Richards, Tantalum Based Superconducting Tunnel Junctions for Low-Noise, SIS Millimeter Wave Receivers, 1985 US-Japan Workshop on Josephson Junction Electronics, Kauai, Hawaii, June 18-19, 1985.

A. V. Räisänen, D. G. Crété P. L. Richards, and F. L. Lloyd, Wide-Band Ultra Low Noise mm-Wave Mixers with a Single Tuning Element, 16th European Microwave Conference, Dublin, Ireland, 8-12 September 1986.

G.-J. Cui, D. W. Face, E. K. Track, D. E. Prober, A. V. Räisänen, D. G. Crété, and P. L. Richards, High Quality Ta/PbBi Tunnel Junctions for 85-110 GHz SIS Mixer Experiments, Applied Superconductivity conference, Baltimore, Maryland, 9/28-10/3/86.

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Statement

There were no inventions or patents disclosures during this grant period.